Short-term study and light curve analysis of eclipsing variable star TOI-2109b

Helena Rose Fleming

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Abstract

In this study, we present an attempt at detection of the exoplanet transit of TOI-2109b, a gas giant planet orbiting an F-type star [6][11], using a ground-based telescope in Big Hill, Kentucky [9] and a CCD camera. We used relative photometry techniques to analyze several transit events of TOI-2109b. Only one detection was fruitful due to technical issues. We retrieved one usable light curve, which we feel is, due to the error margin of the data, not enough to say that we have measured the transit.

1 Introduction

The study of exoplanets, planets orbiting stars beyond our solar system, has revolutionized our understanding of the cosmos. Among the techniques used to identify and characterize these planets, the method of conducting photometry on exoplanet transit stars has emerged as a tool in unveiling their presence and potentially even unveiling their physical characteristics. This is the significance of using relative photometry methods to construct the light curve of TOI-2109b. In this paper I discuss the methods used, the data collected, and the significance of various aspects of the photometric process.

2 Exoplanet Transits

Exoplanet transits happen when a planet passes in front of its host star as observed from here on Earth, leading to a reduction in the star's brightness, like a celestial eclipse. Detecting these events can provide information about the planet, including its size, orbital period, and proximity to the host star. [3]

To identify exoplanet transits, we employ ground-based telescopes, space-based observatories, and technology such as Charge-Coupled Device (CCD) cameras. This approach has evolved and has uncovered many exoplanets, expanding our knowledge of planets beyond our solar system.

2.1 TOI-2109b

In the context of exoplanet transits, TOI-2109b stands as an example of the discoveries made in the realm of exoplanetary astronomy. TOI-2109b is a gas giant exoplanet orbiting an F-type star, and its detection is a testament to the effectiveness of transit methods.

The discovery of TOI-2109b was announced in a study published by Ian Wong et al. in "The Astronomical Journal" in 2021 [10]. The exoplanet's physical characteristics and properties were scrutinized through the observation and analysis of its transits, revealing an understanding of this distant world.

The TOI planets, a subset of exoplanets observed and documented by the Transiting Exoplanet Survey Satellite (TESS), have opened up possibilities in our exploration of exoplanetary systems. Launched by NASA in April 2018, the TESS mission is a space-based observatory, much like the Hubble telescope, designed to survey the entire sky, focusing on the brightest stars in each sector. TESS employs the transit method, monitoring stars for dimming patterns caused by the passage of exoplanets in front of their host stars. These discoveries have expanded our catalog of exoplanets.[3][4]

2.1.1 Physical Qualities of TOI-2109b

TOI-2109b orbits its F-type host star with a period of approximately 0.67 days, indicative of its proximity to the host star. This orbital configuration, along with precise transit observations, allowed astronomers to estimate its radius and density, providing insights into its composition and potential atmospheric properties.[5]

The Ian Wong et al. study found that TOI-2109b is a gas giant, with a radius about 1.347 ± 0.047 times that of Jupiter.[10] This determination is fundamental in classifying the planet and understanding its likely composition. Additionally, the study presented further information on the planet's equilibrium temperature and other essential parameters contributing to our comprehension of its physical nature and environment.

Exoplanet transits have been a useful tool in the exploration of solar systems beyond our home of the Milky Way, the discovery of TOI-2109b being an example of their effectiveness. The study of exoplanets like TOI-2109b not only enhances our knowledge of exoplanetary systems as a scientific concept but also holds the potential to uncover the conditions necessary for the existence of life beyond Earth, though that is far beyond the scope of this paper and the scope of this author's knowledge on extraterrestrial life.

Below is the mathematical methodology used in the Wong et al study. This "sinusoidal phase-curve model that treats the stellar and planetary fluxes separately"[10] helped to dissociate ellipsoidal distortion and tidal response to stellar gravitation.

$$F_*(t) = 1 - A_{\text{ellip}} \cos(2\phi) + A_{\text{Dopp}} \sin(\phi). \quad (1)$$

$$F_p(t) = \bar{f}_p - A_{\text{atm}} \cos(\phi + \psi), \quad (2)$$

$$F_*(t) = 1 - A_{\text{ellip}} \cos(2\phi) + A_{\text{Dopp}} \sin(\phi). \quad (3)$$

Characterization outside the light curve itself was completed for TOI-2109b primarily using external spectra and other data available [10]. See references to view the study.

3 Methodology

The observations of TOI-2109b were conducted using the PlaneWave CDK500 telescope,[7] housed in a observation dome. With a 0.5-meter aperture, this telescope provided adequate spatial resolution, enabling us to capture details of the exoplanetary system.

In conjunction with the telescope, we employed the AIS Apogee ALTA Model U9000X camera, [2] a specialized CCD camera designed for astrophotography and scientific imaging. This camera offers high quantum efficiency and low noise, ideal for capturing variations in stellar brightness during exoplanet transits. The U9000X camera's sensor and sensitivity played a critical role in obtaining images with minimal noise.

We took CCD measurements of the target star in a series of ten images every ten to fifteen minutes. I refer to the series of ten measurements as an 'imaging burst'

3.1 Calibration Data

To ensure the accuracy of our observations and analysis of TOI-2109b's transits, we employed standard image reduction techniques. Dark frames quantify and subtract the camera's electronic noise, providing a reference for noise introduced by the camera. Flat frames account for pixel sensitivity variations across the sensor, ensuring uniformity in images. Bias frames capture the zero-exposure level of the camera, crucial for removing constant offsets.

3.2 challenges

Despite meticulous calibration, challenges arose during our observations of TOI-2109b. Telescopic mirrors accumulate dust, degrading image quality. Contaminants on the telescope's primary mirror scattered incoming light, affecting image quality. Light pollution from nearby sources interfered with the astronomical observations as well, elevating background light levels and complicating calculation of faint pixel saturation differentials. The camera needed to capture pixel saturation data at a level easily compared to background sky light radiation, due to the incoming light scatter and debris this data was affected.

4 Results

A dataset was generated, consisting of time-series images capturing the star's brightness variations during exoplanet transits. These images were processed and analyzed to construct precise light curves, necessary for confirming the planet's passage. The following data was included in our study: Julian Date, Relative Flux, Comparison Star Relative Flux, and relative flux error.

Further, we divided the relative flux of our target star by the average relative flux of the comparison stars for each of the measurements. We repeated this process for the measurements after averaging the imaging bursts together. Thus, we retrieved the apparent magnitude of TOI-2109b in each measurement and for the averaged data, in each of the imaging bursts.

1. Julian Date 240000: The JD time at which each image was captured, providing the temporal context for the observations.

2. Relative Flux: The measured flux of the target star (the host star of TOI-2109b) in each image.

3. Comparison Star Relative Flux: The measured flux of one or more comparison stars in the same images. Comparison stars serve as reference sources, allowing us to correct for atmospheric conditions.

4. And finally the relative flux error of both the target star and the comparisons.

4.1 Selection of Comparison Stars

Appropriate comparison stars are critical for photometric analysis of exoplanet transits. In this study, three comparison stars (C1, C2, C3)(TYC

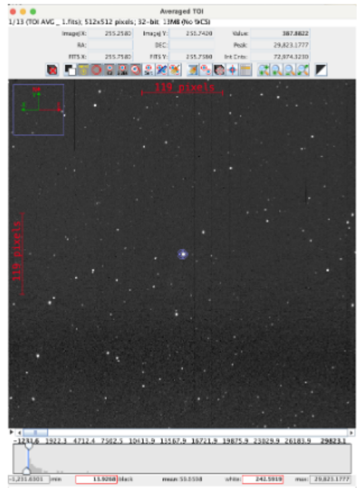

Figure 1: The starfield as seen within the AstroImageJ software, preceding relative photometry

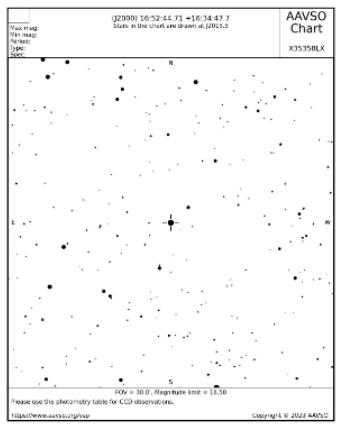

Figure 2: Star Chart, via AAVSO [1]

1521-68-1, 2MASS J16530152+163450, 2MASS J16530524+1633356; respectively) were selected based on stability (non-variability) and proximity to the target star, minimizing errors in differential photometry.

As seen in figures one and two, we compared the starfield visible in our CCD measurements to the star chart for TOI-2109b from AAVSO [1] in order to find comparison stars and to ensure we captured data on the correct star. We also used simbad to locate proper comparison stars [8]

5 Discussion

Issues with calibration data, mirror contaminants, and a dying camera chip affected observations. Further evidence is needed to confirm TOI-2109b's transit. Improvements in observational techniques, mirror maintenance, and additional observations across multiple nights are essential. Imaging bursts in future observations at windswept should be no more than five minutes apart, and should consist of no less than fifteen measurements. Expanding observations into multiple wavelength bands could also provide additional information on the exoplanet's atmosphere.

5.1 Graphical Data

As can be seen in our graphical data, there is a significant dip which could reasonably be called an exoplanet transit, however, our margin of error is far too high to make that assertion with the level of certainty necessary. The fluctuations anticipated of the target star fall within the range of uncertainty, so despite the

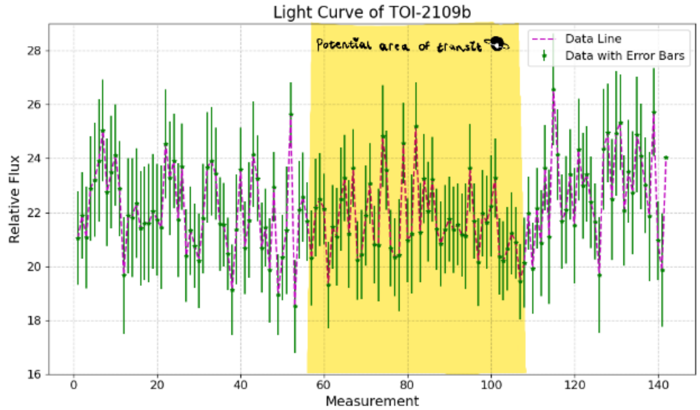

Figure 3: Results that have not yet been averaged, this graph displays the relative flux of TOI-2109b on the y-axis and individual measurement steps on the x-axis. The presumed area of transit detection is highlighted in yellow.

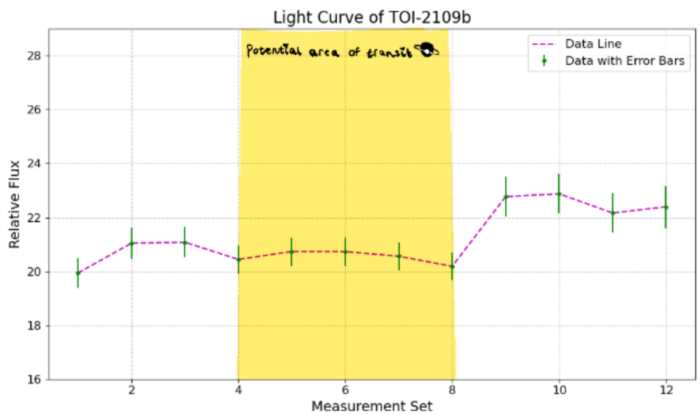

Figure 4: Averaged Data set, with transit detection area highlighted as in figure 3. Each measurement in the imaging burst was added together and divided by ten. The average Julian Date has been replaced by measurement set ('Imaging Burst')

appearance of a transiting planet light curve we can only speculate that the passage of TOI-2109b in front of its host star was captured. This is especially visible in figure 3, where the error bars seemingly overtake the graph itself.

5.2 The need for further evidence

The identification of exoplanet transits is a meticulous process that requires significant evidence to confidently confirm their presence. While the observations conducted in this study suggest a possible detection of TOI-2109b's transit, it is crucial to emphasize that additional evidence is necessary to confirm the transit beyond any reasonable doubt. The transit signal should be reproducible across multiple observing runs and independent analyses to reduce the risk of false positives. Hopefully, more amateur astronomers go on to study this transiting planet to further confirm its status and contribute their findings to the AAVSO.

5.3 Areas For Improvement

To enhance the reliability and robustness of exoplanet transit detection and confirmation, several areas can be improved. Replicating observations across multiple nights and under varying conditions can help confirm the presence of the transit signal. Consistency in data collection is essential for establishing the repeatability of the observed events. In this summer we only managed to collect one night worth of data on TOI-2109b. Other nights suffered from issues regarding our technology, the weather, or simply not being able to make it to the telescope. Implementing thorough

mirror and instrument maintenance (even in the off-seasons for Windswept) to minimize the presence of contaminants is crucial. Routine cleaning and calibration will enhance the quality of future observations. Expanding observations into multiple wavelength bands, such as through the use of filters, could potentially provide future Berea Astronomers additional information on the exoplanet's atmosphere and properties. Future researchers can also employ more advanced statistical techniques to further validate transit detections and distinguish them from false positives. Perhaps using python to parse the data, working more on the data side of AstroImageJ, or if one is so inclined perhaps making an even more specialized software.

While the initial data suggests the possibility of detecting TOI-2109b's transit, it is necessary to exercise caution and seek additional evidence before confirming this finding. The optimization of observational and data processing techniques can contribute to more reliable and precise results in the field of exoplanet research. We do not feel comfortable suggesting we have, with any certainty, detected the transit of TOI-2109b at this time.

Future researchers are encouraged to take longer imgaging bursts with far less down time between bursts, to clean the mirror before and after research seasons, to replace the chip in the CCD camera or simply purchase a new CCD, and remove the light source directly outside the observation dome.

6 Conclusion

This study represents an effort to detect the exoplanet transit of TOI-2109b, contributing to our understanding of exoplanetary systems. The inconclusivity of our findings displays the complexities in exoplanet detection, highlighting the importance of meticulous data collection and analysis. Studies like this contribute to the foundation of knowledge in exoplanet research.

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